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ABSTRACT

Wild pigs (*Sus scrofa*) are a destructive invasive species that cause extensive damage to agriculture throughout many regions of the world. In particular wild pigs damage corn more than any other crop, and most of that damage occurs immediately after planting when wild pigs excavate and consume planted seeds. We evaluated whether anthraquinone (AQ), a repellent, could be useful for protecting seed corn from consumption by wild pigs. Specifically, we conducted cafeteria-style tests at 16 bait sites for 6 nights using concentrations of: untreated, 0.5, 1.5, and 3.0% AQ by weight sprayed on whole-kernel corn in AL and TX, USA. We found that repellency for wild pigs was dependent on the AQ concentration, with the greatest repellencies of 95% (AL) and 59% (TX) observed using ~3% AQ. We also found that repellency decreased as the abundance of wild pigs increased at the bait sites. Raccoons (*Procyon lotor*) did not appear to be repelled by the AQ-coated corn, but white-tailed deer (*Odocoileus virginianus*) and mule deer (*O. hemionus*) were. Overall, our results show promise for the development of a repellent for treating seeds to protect them from wild pigs. We recommend the next steps of testing of the 3% concentration of AQ on corn seeds that are planted underground to optimize the best potential protection against damage from wild pigs.

1. Introduction

Wild pigs (*Sus scrofa*), also referred to as feral hogs, feral pigs, feral swine, invasive wild pigs, or wild boars (Keiter et al., 2016), are a widely distributed and destructive invasive species throughout parts of North America, Australia, South America, Africa, and many island nations (Barrios-Garcia and Ballari 2012). In particular, populations of wild pigs have been rapidly increasing and expanding throughout North America during the last 5 decades (Bevins et al., 2014; Michel et al., 2017; Snow et al., 2017). Wild pigs cause extensive damage to agricultural and ecological resources (Hone 1995; Pimentel 2007; Anderson et al., 2016), and these damages are expensive to mitigate (Pimentel 2007). The most common method for reducing damage is lethal population control of wild pigs, which includes trapping, snaring, recreational hunting, professional sharpshooting, and aerial shooting (Coblentz and Baber 1987; Choquenot et al., 1993; Mayer and Brisbin 2009; Ditchkoff and Bodenchuk 2020). Despite these measures, damage to agriculture from wild pigs remains a major challenge to growers (Boyer et al., 2020; Strickland et al., 2020).

Wild pigs reportedly cause more damage to corn than any other type of crop (Schley et al., 2008; Anderson et al., 2016). In a survey of 11 states in the USA during 2014, Anderson et al. (2016) estimated that damage to corn resulted in a loss of $61.7 million (USD). Wild pigs use corn as a food resource and as shelter (Schley et al., 2008; Strickland et al., 2020). Damage to corn tended to occur during two primary growth stages, immediately following planting and once again after the ears matured (Boyce et al., 2020). Most damage occurred immediately after planting when wild pigs consumed the freshly planted and germinated seeds of corn plants (Boyce et al., 2020; Strickland et al., 2020). Finding methods that protect the seeds of corn plants (hereafter; seed corn) until emergence could substantially reduce the amount of damage observed in corn fields.

Few repellents have been tested for wild pigs, and repellents are not currently considered a viable option for management of wild pig damage (Ditchkoff and Bodenchuk 2020). A small number of olfactory or gustatory repellents containing predator odors or bitter tasting agents, respectively, are commercially available in Europe but have proven ineffective (Vilardell et al., 2008; Schlageter and Haag-Wackernagel 2012a;b). However, a pilot study using anthraquinone (AQ) as a seed corn treatment showed promise for reducing consumption by wild pigs

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(Santilli et al., 2005). Those researchers showed that a 0.64% (6400 mg/kg) concentration of AQ on whole-kernel corn presented in nylon sheets on the ground was effective at reducing consumption by 86.5% for three adult wild pigs.

Anthraquinone is a chemical repellent that causes post-ingestional distress by irritating the gut, and has been used as a repellent to protect crops primarily from birds since the 1940s (DeLiberto and Werner 2016). Anthraquinone has been used to protect seed corn from pest species with varying degrees of success (Werner et al., 2009; DeLiberto and Werner 2016), suggesting that differing concentrations may impact effectiveness. Pest species must consume enough AQ to induce a negative post-ingestive response, and therefore the repellency is considered a learned behavior (Werner and Provenza 2011).

Our objectives were to evaluate whether seed corn treated with an AQ-coating reduced consumption by populations of free-ranging wild pigs, and to identify the most effective concentration of AQ for repelling wild pigs from consuming the seed corn. We conducted a series of cafeteria-style tests with free ranging wild pigs in AL and TX, USA. Results from this study will inform future product development for a readily applied seed treatment that may be effective as reducing damage from wild pigs to newly planted seeds.

2. Methods

2.1. Study area

The first field trial was conducted during August 2019 in southern AL, USA (Fig. 1). The temperature averaged 27.6 °C and 120.9 mm of

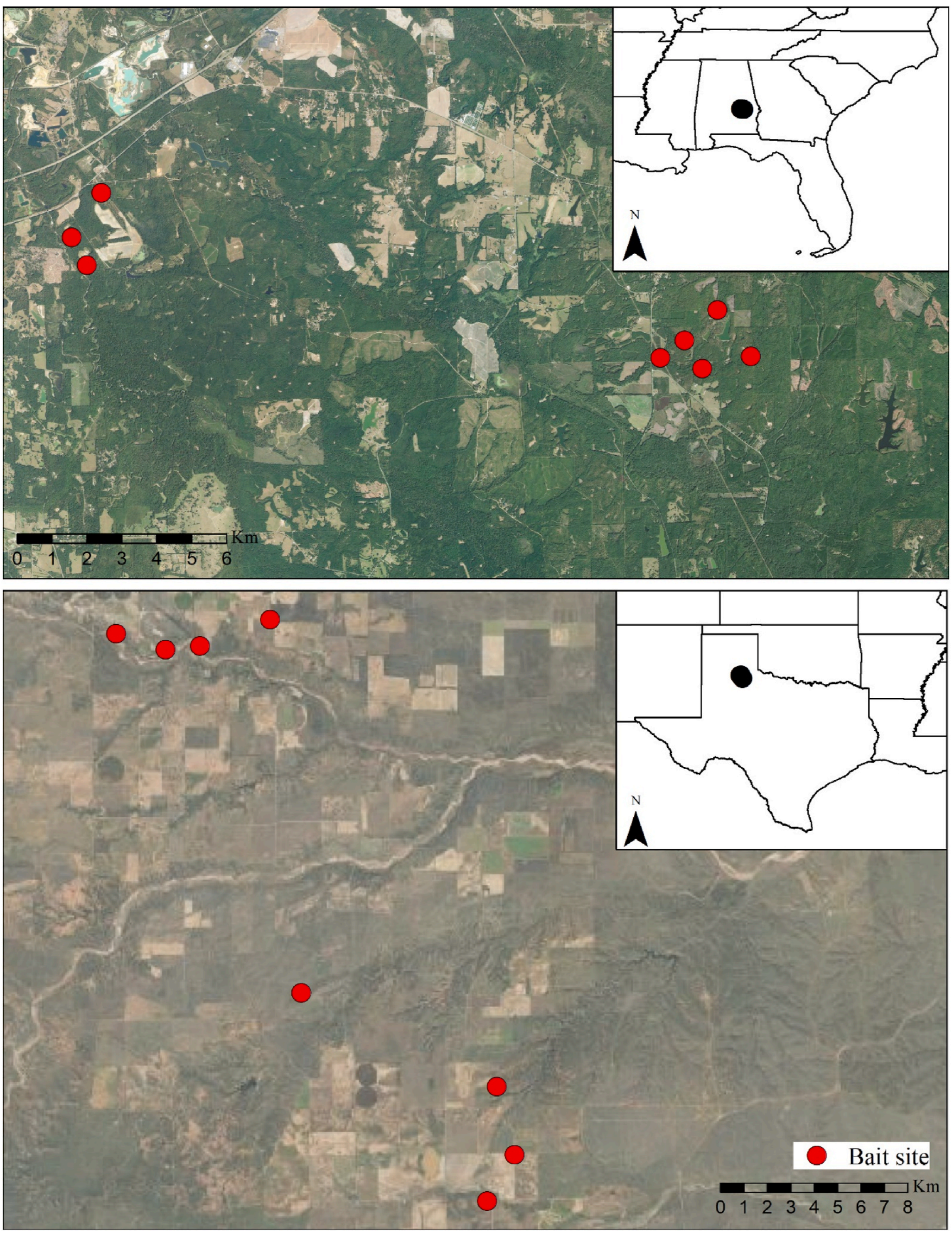

Fig. 1. Study areas and baiting locations for cafeteria-style preference testing of different concentrations of anthraquinone treated whole-kernel corn for free-ranging wild pigs in AL, USA (August 2019) and TX, USA (March 2020).

precipitation occurred (https://www.wunderground.com/history). The landscape is characterized as part of the southeastern plains ecoregion; a mosaic of croplands, pasturelands, and woodland forests that are a mixture of oak (*Quercus* spp.), hickory (*Carya* spp.), and pine (*Pinus* spp.) forest (Bailey 1980, 1998). The second field trial was conducted in north-central TX during February and March 2020. The temperature averaged 5.5 °C, and 13.0 mm of precipitation occurred (https://www.wunderground.com/history). The landscape is characterized as part of the southwestern tablelands ecoregion, dominated by juniper (*Juniperus* spp.), scrub oak (*Quercus* spp.), and midgrass savanna (Bailey 1980, 1998) with interspersed croplands. The potential population density of wild pigs in 2016 was predicted at 6–8 wild pigs/km^2 in AL and 3–5 wild pig/km^2 in TX (Lewis et al., 2019). It was also estimated that 0.93% ($1949 USD) of corn crops were lost to wild pigs in AL, and 1.65% ($23,884 USD) were lost to wild pigs in TX during 2014 (Anderson et al., 2016).

2.2. Study design

We began each study prebaiting sites for five nights to locate wild pigs. We selected sites with fresh sign of wild pigs (e.g., wallows, rooting, tracks, and feces) and placed ~11 kg of whole-kernel corn and a remote camera (RECONYX PC900, RECONYX, Inc., Holmen, WI, USA) mounted on T-posts 5 m away. We refreshed the whole-kernel corn and checked the camera images daily. We also constructed ~5 × 5 m fences of 3-strand barbed wire around the piles of whole-kernel corn to exclude cattle as needed, with wires strung at ~40 cm, ~70 cm, and ~100 cm above ground. We pre-baited ~20 sites in AL and ~30 sites in TX until we found sufficient, independent sounders of wild pigs for commencing the study in each area (i.e., eight sites with independent sounders of wild pigs in each study area). We identified independent sounders by recording sizes, colors, patterns, numbers, and sexes of wild pigs observed in camera images at each site and comparing with other sites. The distance between the nearest sites in AL averaged 1091 m (SE = 92.4), and in TX averaged 2607 m (SE = 695.8).

Once eight bait sites were identified in each study area, we initiated a cafeteria-style preference test on night six at each bait site. At each site we offered three treatment concentrations (ranging from 0.5 to 3.0%; see details below) of AQ sprayed and dried on whole-kernel corn. All treatments were formulated using a commercial seed treater to apply an aqueous suspension of the AQ-based repellent on whole-kernel corn. Treatment concentrations were calculated as the percentage of AQ by weight from the total weight of the whole-kernel corn plus the coating. In AL, we tested a large range of concentrations to ensure that AQ had an effect on consumption by wild pigs. In TX, we used a narrower range of concentrations based on results from AL, with the goal of identifying a threshold in repellency using minimal AQ-coating. The treatments offered in AL included: 1) 0.5% AQ by weight, 2) 3.0% AQ weight, and 3) a control treatment of whole-kernel corn without a coating. Based on results from AL, we increased the lower concentration treatment for evaluation in TX to increase the repellency of that treatment. The treatments offered in TX included: 1) 1.5% AQ by weight, 2) 3.0% AQ by weight, and 3) a control treatment of whole-kernel corn without a coating. We conducted a chemical analysis of the treatments using high-performance liquid chromatography to verify the concentrations of AQ used in this study.

We designed the cafeteria-style preference test so that wild pigs at each bait site would encounter all three treatments and choose to consume whichever treatment they preferred (Fig. 2). We spaced the three treatments 10–20 m apart from each other, and placed remote cameras 5 m from each treatment so we could identify which treatment wild pigs were visiting without ambiguity (i.e., the field of view from each camera only captured the immediate proximity around a single treatment). We deployed each of the treatments in a triangular pattern with the cameras facing out from the center (Fig. 2a), except where the bait site was along a linear feature of the landscape such as a fence line (Fig. 2b) in which case cameras and bait sites were linearly aligned.

All treatments were offered in wood or plastic troughs which measured 38 × 106 × 9 cm with an open top. The troughs were staked to the ground so wild pigs could not move or flip them over. During the hours of 0800–1600, we placed ~11 kg of each treatment into respective troughs for each treatment night. Following each treatment night, we removed any remaining treated whole-kernel corn from within and outside of each trough. We weighed the remaining corn for each treatment and placed a fresh ~11 kg of each treatment back into the respective troughs. We repeated this procedure for six consecutive nights, and we made no attempt to exclude non-target wildlife from the troughs. We compared the responses of wild pigs and non-target wildlife (see Data Analysis below) to treatments within study areas and not between, because we could not control for varying densities of animals and environmental influences between areas.

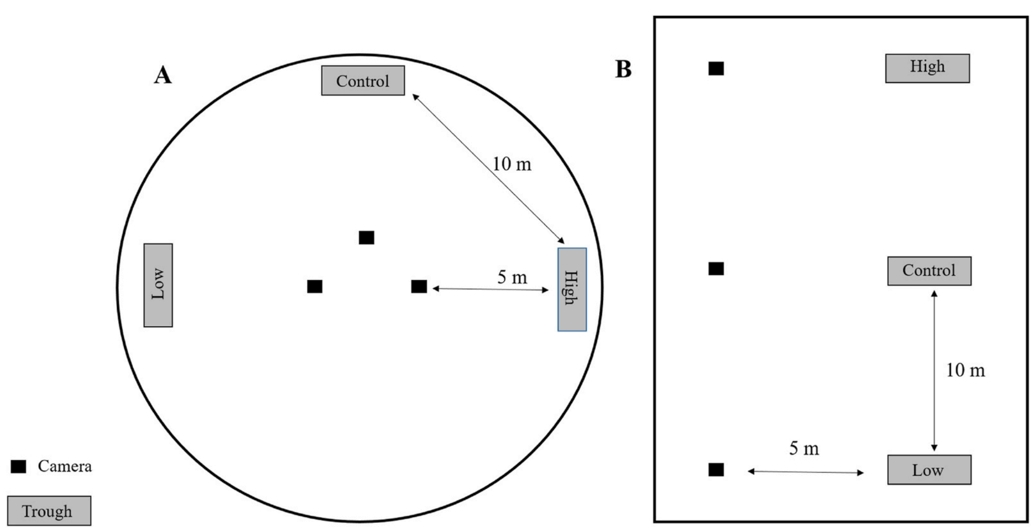

Fig. 2. Bait site layouts for cafeteria-style preference testing of different concentrations of anthraquinone treated whole-kernel corn for free-ranging wild pigs in AL, USA (August 2019) and TX, USA (March 2020). Layout A was used in most situations. Layout B was used if the bait site was along a linear feature of the landscape (e.g., along the edge of an agricultural field or fence).

2.3. Remote camera monitoring

For each trough we mounted a remote camera 5 m away, 1.5 m high on a T-post, and angled down at 70° to create a consistent field of view (Fig. 2). The remote cameras were set to record time-lapse images every 3 min when triggered. We processed all time-lapse images using the Colorado Parks and Wildlife Photo Warehouse database (Ivan and Newkirk 2016), which allowed single-observer viewing of images, recording of data, and tabulating into a database. For each image we recorded the date, time, count of each species present, and count of each species consuming bait from the troughs (i.e., head positioned over the trough or birds perched on/in the trough). All animals observed were identified to the species level, with the exception of grouping all passerine birds into a single category (i.e., passerines), and we grouped mule deer (*Odocoileus hemionus*) and white-tailed deer (*O. virginianus*) into a single category (i.e., deer), respectively. Overall, in AL we collected and examined 67,644 images and in TX we collected and examined 65,990 images.

2.4. Data Analysis

For each study area, we compared the amount of each treatment consumed throughout the study duration using a linear mixed model from package lme4 (Bates et al., 2014) in Program R (v 3.6.3, The R Foundation for Statistical Computing). The full model examined was Amount Consumed (kg) ~ Treatment + Night + Treatment × Night. We also tested reduced models where we removed the interaction term to best interpret the unconditional main effects (Engqvist 2005). We considered the low-treated corn as the reference treatment in these models for comparing with the high-treated and untreated treatments, respectively. We modeled Site ID as a random intercept to account for repeated measures taken at each site. We examined the 95% confidence intervals (CIs) surrounding the parameter estimates for a lack of overlap of zero to indicate statistically and biologically significant effects (Burnham and Anderson 2002; Anderson 2008).

From the remote camera images for each study area, we compared the average number of each species observed feeding per hour (i.e., hourly rate) among the treatments using similar linear mixed models as described above. Specifically, we examined the hourly rate for wild pigs, raccoons (*Procyon lotor*), and deer, as these species represented 98.1% of the images with animals feeding in AL, and 90.9% in TX. We considered the untreated corn treatment as the reference treatment in these models to compare with the high- and low-treated treatments, respectively.

Finally, we evaluated whether an index of the abundance of wild pigs observed at bait sites influenced how much of each treatment was consumed. Specifically, we averaged the maximum count of wild pigs observed in a single image per treatment per bait site across the six nights the treatments were offered. We used the maximum count as a conservative estimate of the abundance of wild pigs at each treatment. Across the six nights we similarly averaged the amount of consumption per treatment per bait site (i.e., 3 treatments × 16 bait sites = 48 observations). We used a simple linear model from the base package in Program R to examine whether the average consumption of each treatment was influenced by the average maximum number of wild pigs observed.

3. Results

Chemical analyses of AQ concentration used as the AL high-treated corn was 3.04% (SD = 0.007). We inadvertently used all the low-treated corn in AL and thus could not conduct chemical analysis to confirm concentration. The low-treated corn in TX was 1.49% (SD = 0.005) and the high-treated corn was 3.23% (SD = 0.003). At one bait site in TX cattle broke through our exclusion fence three nights in a row and ate most of the treated and untreated corn, therefore we excluded these nights from analysis for that site.

3.1. Consumption

In AL, we observed an overall average consumption of 0.4 kg (proportion = 0.04; SE = 0.02) of high-treated corn, 3.5 kg (proportion = 0.36; SE = 0.06) of low-treated corn, and 7.5 kg (proportion = 0.75; SE = 0.05) of untreated corn each night. There were no significant interactions between treatment and night. When we removed the interaction term from the model, the reduced model indicated that low-treated corn was consumed less than untreated corn (β = −3.91; 95% CI = −2.78 to −5.03; *P* < 0.001), and high-treated corn was consumed less than low treatment (β = −3.17; 95% CI = −4.31 to −2.05; *P* < 0.001). Compared to untreated corn, high-treated corn was consumed 95.0% less and low-treated corn was consumed 52.3% less. We found no evidence that consumption differed across nights (β = 0.14, 95% CI = −0.13–0.41; *P* = 0.305; Fig. 3).

In TX, we observed an overall average consumption of 3.6 kg (proportion = 0.36; SE = 0.05) of high-treated corn, 5.1 kg (proportion = 0.51; SE = 0.06) of low-treated corn, and 8.8 kg (proportion = 0.87; SE = 0.04%) of untreated corn each night. There were no significant interactions between treatment and night. When we removed the interaction term from the model, the reduced model indicated that low-treated corn was consumed less than untreated corn (β = −3.67; 95% CI = −2.43 to −4.90; *P* < 0.001), and high-treated corn was consumed less than low-treated corn (β = −1.50; 95% CI = −2.73 to −0.26; *P* = 0.019). Compared to the untreated corn, high-treated corn was consumed 58.7% less and low-treated corn was consumed 41.7% less. We found no evidence that consumption differed across nights (β = 0.22, 95% CI = −0.07–5.07; *P* = 0.141).

3.2. Wild pig feeding

In AL, we found a significant interaction between the high treatment and night, where the rate of wild pigs feeding on high-treated corn was lower during latter nights (β = −0.42; 95% CI = −0.78 to −0.06; *P* = 0.026; Fig. 4). When we removed the interaction term from the model, we found that the rate of feeding on high-treated corn was lower than untreated corn (β = −2.08; 95% CI = −2.71 to −1.46; *P* < 0.001), and there was no difference rates between low and untreated corn (β = −0.50; 95% CI = −1.13–0.13; *P* = 0.121). There was also no difference in the rate of wild pigs feeding amongst the 6 nights (β = 0.14; 95% CI = −0.01–0.29; *P* = 0.077).

In TX, we found no significant interactions between treatment and night. When we removed the interaction term from the model, we found the rate of feeding on high-treated corn was lower than untreated corn (β = −0.97; 95% CI = −1.88 to −0.05; *P* = 0.041). Wild pigs were observed feeding on low-treated corn at similar rates to untreated corn (β = 0.02; 95% CI = −0.89–0.94; *P* = 0.962). There was also no difference in the rate of wild pigs feeding amongst the 6 nights (β = 0.20; 95% CI = −0.02–0.42; *P* = 0.074).

The average maximum numbers of wild pigs observed when present were 5.3 (SE = 0.4) in AL and 8.3 (SE = 0.4) in TX. We found that high-treated corn was consumed more when more wild pigs were present (β = 0.07; 95% CI = 0.06–0.08; *P* < 0.001). We also found similar relationships for low-treated corn (β = 0.08; 95% CI = 0.06–0.11; *P* < 0.001), and untreated corn (β = 0.03; 95% CI = 0.02–0.05; *P* < 0.001).

3.3. Other species feeding

For raccoons and deer in AL, we found no significant interactions between treatment and night. When we removed the interaction term from both models, we found no differences the rates of feeding between for the high- (β = −0.36; 95% CI = −1.13–0.41; *P* = 0.362) and low-treated corn (β = 0.66; 95% CI = −0.11– 1.44; *P* = 0.095), respectively, compared to the untreated corn for raccoons. Deer were rarely observed by our cameras (Fig. 4), but nonetheless we found a lower rate of feeding on high- (β = −0.04; 95% CI = −0.08 to −0.01; *P* = 0.013)

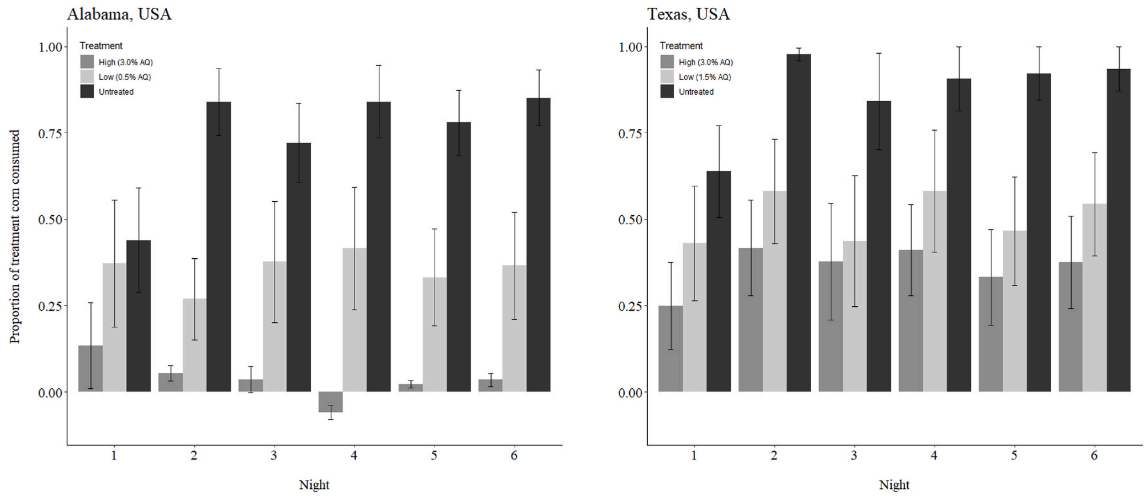

Fig. 3. Proportional amount of consumption recorded for each treatment of anthraquinone (AQ) sprayed onto whole-kernel corn in AL, USA (August 2019) and TX, USA (March 2020). The remaining corn on night 4 in AL was wet from rain. Error bars are standard errors.

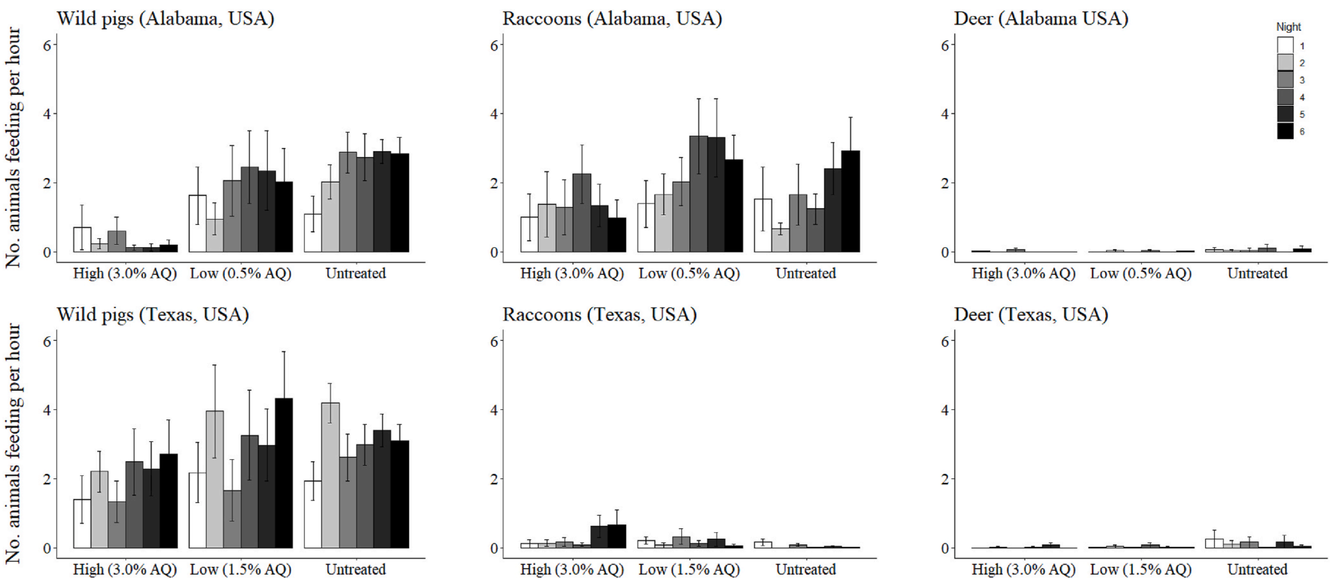

Fig. 4. Amount of feeding per hour recorded for wild pigs, raccoons, and deer (white-tailed deer and mule deer) for each treatment of anthraquinone (AQ) sprayed onto whole-kernel corn in AL, USA (August 2019) and TX, USA (March 2020). An animal was considered feeding if its head was over or in the trough containing the corn.

and low- (β = −0.04; 95% CI = −0.08 to −0.007; P = 0.021) treated corn compared to the untreated corn, respectively.

For raccoons and deer in Texas, we found a significant interaction where the rate of feeding by raccoons (β = 0.14; 95% CI = 0.04–0.32; P = 0.006) and deer (β = 0.03; 95% CI = 0.002–0.06; P = 0.038) were greater on the high-treated corn in the latter nights of the study, respectively. When we removed the interaction term from each model, the rate that raccoons fed on the high-treated corn was lower than the untreated corn (β = 0.25; 95% CI = 0.08–0.42; P = 0.005). The rate raccoons fed on the low-treated corn and untreated corn were similar (β = 0.13; 95% CI = −0.04–0.29; P = 0.146). The rates that deer fed on the high- (β = −0.11; 95% CI = −0.16 to −0.05; $P < 0.001$) and low- (β = −0.10; 95% CI = −0.15 to −0.04; P = 0.001) treated corn were lower than the untreated corn, respectively.

4. Discussion

Our results showed that AQ-coating sprayed on whole-kernel corn reduced consumption by wild pigs, and the reduction was influenced by the concentration of AQ used. The greatest reduction in consumption occurred with the highest concentration tested (~3% AQ), and represented 95% and 59% repellency in AL and TX, respectively. The lower concentrations of 0.5% and 1.5% AQ had 52% and 42% repellency, respectively. These trends in repellency were likewise observed in the rate that wild pigs spent feeding on each of the treatments, with greater AQ concentrations corresponding to lower rates of feeding by wild pigs. These results are promising, suggesting that an AQ-coating on seed corn may be useful for reducing the amount of damage caused by wild pigs after planting.

Despite the promising results, the repellency observed in our study was less than the original pilot study with wild pigs in pens, which found a lower concentration of AQ (0.64%) induced ~87% repellency (Santilli et al., 2005). This disparity may indicate that repelling free-ranging wild pigs may require greater concentrations of AQ to be effective. However, our results also indicated that the disparity could be related to the number of wild pigs within a sounder. We showed that consumption of the AQ-treated corn increased when more wild pigs were present, equating to a reduction in repellency as sounder size increased. The trial in Santilli et al. (2005) was limited to only three wild pigs and showed the greatest repellency. Our trials averaged 5.3 and 8.3 wild pigs per bait site in AL and TX, respectively, and we correspondingly observed lower repellency in AL, and even lower repellency in TX with the greatest numbers of wild pigs. Additionally, wild pigs are known to be intra-competitive while foraging especially when resources are limited (e.g., Schnebel and Griswold 1983; Lavelle et al., 2018), which likely resulted in sub-dominant animals feeding more on the higher concentrations of AQ-treated corn than untreated corn as more wild pigs were present.

Our results also demonstrate some interesting findings for raccoons and white-tailed deer. Raccoons did not appear to be repelled by any of the AQ treatments, and actually spent more time feeding on the highest treatment in TX. Therefore, raccoons appeared to not be sensitive to AQ. However, Snow et al. (in press) showed that wild pigs visited bait sites most during dusk, whereas raccoons visited most during night. Also, raccoons avoided bait sites when wild pigs were present. Therefore it is likely that raccoons were visiting the bait sites after wild pigs had visited and consumed the untreated corn, leaving only the AQ-treated corn for raccoons. More investigation without wild pigs present would be needed to confirm. Finally, deer visits were rare, but followed the expected trend of declining visitation based on the increasing concentration of AQ treatments. These results are important for agricultural growers because raccoons and deer can cause substantial damage to corn fields (Humberg et al., 2007; Boyce et al., 2020).

This study was useful for determining the potential utility of using AQ to protect seed corn by repelling wild pigs, some limitations exist. For example, in this study each of the treatments were offered in a large pile above ground where wild pigs had quick and easy access. It is unknown if this repellency can be extrapolated to the more realistic situation of wild pigs rooting up single seeds after planting. It is also unknown how long the AQ-coating on the treated seeds would stay viable once planted.

5. Conclusion

This study confirmed the utility of an AQ-coating to repel wild pigs from consuming whole-kernel corn. Next steps include testing of the highest concentration of AQ (e.g., ~3%) on seed corn that is planted in the ground, and monitoring for potential protection against damage from wild pigs. It will also be important to determine the duration of protection that AQ may provide on treated seeds once underground. We also recommend the next studies are conducted during planting seasons, to ensure any seasonal variation is accounted for.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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